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2.2.0 Reactivity Balance Calculations

Learning Objectives:

1. Relate a change in a plant parameter to its effect on estimated critical rod position (ECP).
2. Relate a change in a plant parameter to its effect on estimated critical boron concentration.
3. Relate a change in a plant parameter to its effect on the value of shutdown margin.

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2.2.1 Introduction

The plant reactivity procedure provides guidance for the calculation of estimated critical positions, estimated critical boron concentrations, and shutdown margins, and for the analysis of reactivity anomalies. All of these calculations are safety-related and are addressed in plant technical specifications. These calculations are described in the following paragraphs of this section.

2.2.2 Estimated Critical Position

The purpose of the calculation is to ensure that core criticality occurs with an optimum control rod position. The calculation of the ECP may be performed with two different methods. These are the $\Delta\rho$ method and the reactivity balance method. The basis of both calculations is that core reactivity is equal to zero when the reactor is critical.

2.2.2.1 $\Delta\rho$ Method

In order to calculate an ECP with the $\Delta\rho$ method, a previous critical condition must be known. This previous condition may be an operating situation or data obtained from the startup performed following refueling. Regardless of the source of data, the sum of the reactivity contributions to the previous critical condition (net reactivity) must equal zero. With the subscript 1 indicating a parameter from the previous critical condition, the following relationship holds:

$$\rho_{net_1} = \rho_{power_1} + \rho_{rods_1} + \rho_{boron_1} + \rho_{xe_1} + \rho_{sm_1} = 0 \quad (2.2-1)$$

where:

ρ_{net_1} = algebraic sum of all core reactivity components,

ρ_{power_1} = reactivity contribution from power defect,

ρ_{rods_1} = reactivity contribution based on rod position,

ρ_{boron_1} = reactivity contribution based on boron concentration,

ρ_{xe_1} = reactivity contribution due to Xenon concentration, and

ρ_{sm_1} = reactivity contribution due to Samarium concentration.

Since the net reactivity for the critical condition to be calculated (designated with subscript 2) also must equal zero, it can be expressed as:

$$\rho_{net_2} = \rho_{power_2} + \rho_{rods_2} + \rho_{boron_2} + \rho_{xe_2} + \rho_{sm_2} = 0 \quad (2.2-2)$$

Since both equations equal zero:

$$\rho_{net_1} = \rho_{net_2} \quad (2.2-3)$$

or:

$$\rho_{power_2} + \rho_{rods_2} + \rho_{boron_2} + \rho_{xe_2} + \rho_{sm_2} = \rho_{power_1} + \rho_{rods_1} + \rho_{boron_1} + \rho_{xe_1} + \rho_{sm_1} \quad (2.2-4)$$

Subtracting the terms with subscript 1 from the corresponding terms with subscript 2, equation 2.2-4 becomes:

$$0 = (\rho_{power_2} - \rho_{power_1}) + (\rho_{rods_2} - \rho_{rods_1}) + (\rho_{boron_2} - \rho_{boron_1}) (\rho_{xe_2} - \rho_{xe_1}) + (\rho_{sm_2} - \rho_{sm_1}) \quad (2.2-5)$$

or

$$-\Delta\rho_{rods} = \Delta\rho_{power} + \Delta\rho_{boron} + \Delta\rho_{xe} + \Delta\rho_{sm} \quad (2.2-6)$$

Equation 2.2-6 states that the negative change in reactivity attributable to the change in rod position between the current calculated condition and the previous critical condition is equal to the sum of the changes in reactivity attributable to other factors that have occurred during the time interval between the two critical conditions. The new critical rod position can thus be determined with a rod worth curve.

2.2.2.2 Reactivity Balance Method

With this method, knowledge of a previous critical condition is not required. However, reference conditions for the various reactivity factors and fuel reactivity are required. The reference conditions for the reactivity balance method are:

1. No xenon concentration,
2. No power defect,
3. Control rods completely withdrawn,
4. Boron concentration of zero,
5. No-load T_{avg} , and
6. Equilibrium samarium concentration.

The fuel reactivity (ρ_{fuel}) accounts for the excess amount of fuel (above that required for a critical mass) that is loaded into the core. ρ_{fuel} is usually reduced by the amount of negative reactivity added by the reactor coolant system (RCS) heatup to no-load T_{avg} and by the equilibrium samarium concentration. Also, all startup criticalities are conducted at no-load T_{avg} . Therefore, only deviations from this temperature are considered. With these considerations, the equation for ρ_{net} is:

$$0 = \rho_{net} = \rho_{fuel} - \rho_{rods} - \rho_{boron} - \rho_{xe} - \rho_{sm} - \rho_{mod} \quad (2.2-7)$$

Where:

ρ_{sm} = equilibrium samarium - Present Samarium

ρ_{mod} = No-load T_{avg} - Present T_{avg}

Adding ρ_{rods} to each side of the equation yields the equation for the ECP:

$$\rho_{rods} = \rho_{fuel} - \rho_{boron} - \rho_{xe} - \rho_{sm} - \rho_{mod} \quad (2.2-8)$$

In this equation, the absolute value of reactivity is used. Because of the reference condition conventions, all reactivity additions to the fuel reactivity are expected to be negative, with the exception of the moderator temperature reactivity, which may be either positive or negative. Again, the new critical rod position can be determined with a rod worth curve.

2.2.2.3 Xenon and Samarium Calculations

Changes in xenon and samarium concentrations affect the reactivity added by these fission product poisons. Plant computer programs often provide the xenon and samarium reactivity values.

2.2.3 Estimated Critical Boron Concentration

Many situations arise in which the calculated critical rod position is undesirable (i.e., below the rod insertion limit). In order to achieve criticality at a rod height permitted by the rod insertion limit, the RCS boron concentration must be adjusted. Equations 2.2-5 and 2.2-7 may be solved for boron reactivity instead of rod reactivity. When the algebraic manipulations are made, the equations to determine the estimated critical boron concentration are:

Delta Rho Method:

$$-\Delta\rho_{boron} = \Delta\rho_{power} + \Delta\rho_{rods} + \Delta\rho_{xe} + \Delta\rho_{sm} \quad (2.2-9)$$

Reactivity Balance Method:

$$\rho_{boron} = \rho_{fuel} - \rho_{rods} - \rho_{xe} - \rho_{sm} - \rho_{mod} \quad (2.2-10)$$

The normal procedure is to choose a critical rod position and then adjust the RCS boron concentration to provide the reactivity predicted by equation 2.2-9 or 2.2-10. Once the RCS boron concentration is adjusted to the desired value, the rods are withdrawn until criticality is achieved.

2.2.4 Shutdown Margin

Plant technical specifications contain shutdown margin (SDM) requirements. According to technical specifications:

SDM shall be the instantaneous amount of reactivity by which the reactor is subcritical or would be subcritical from its present condition assuming:

- a. All rod cluster control assemblies (RCCAs) are fully inserted except for the single RCCA of highest reactivity worth, which is assumed to be fully withdrawn. With any RCCA not capable of being fully inserted, the reactivity worth of the RCCA must be accounted for in the determination of SDM; and
- b. In MODES 1 and 2, the fuel and moderator temperatures are changed to the nominal zero power design level.

When the reactor is critical, the shutdown margin is normally ensured by verifying that the shutdown and control banks are withdrawn above the heights specified by the rod insertion limits. However, Limiting Conditions for Operability (LCOs) 3.1.4, 3.1.5, and 3.1.6 require verification of an adequate SDM if any control rod is inoperable or if any bank has been inserted below its rod insertion limit. As a result, it is necessary to be able to calculate the SDM at all times. The value of the shutdown margin **for a critical reactor** is calculated by performing a reactivity balance which accounts for changes from a known critical condition in accordance with the definition of SDM.

$$SDM = |\rho_{rods}| - |\rho_{mod}| - |\rho_{fuel}| \quad (2.2-11)$$

where:

ρ_{rods} = available rod worth, i.e., the negative reactivity that would be added by a trip from the present position, less the value of the most reactive control rod.

ρ_{mod} = the moderator defect, i.e., the positive reactivity added by T_{avg} going from its existing value to the no-load value.

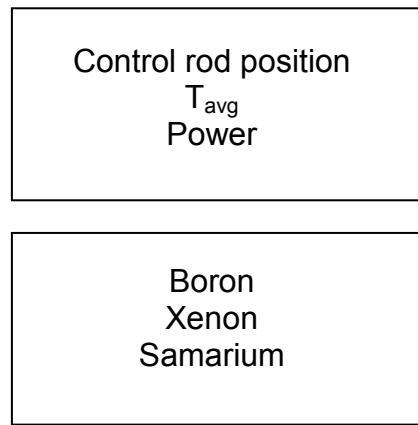
ρ_{fuel} = the fuel temperature (doppler) defect, i.e., the positive reactivity added by power going from the existing value to 0%.

If T_{avg} remains on program, the moderator and the fuel defects can be replaced by the power defect.

The technical specification requirement for an inadequate SDM is to initiate boration. Note that changing the boric acid concentration does not directly change any of the components of the SDM. However, to maintain the reactor critical, one or more of the SDM parameters must change in response to the change in boric acid concentration. The expectation is that the boration will cause control rods to withdraw, thereby increasing the " $|\rho_{rods}|$ " component of the SDM calculation.

Also note that, by itself, a new control rod position, if compensated for by changes in power and/or T_{avg} , does not change the SDM. Since, after rod motion, the reactor will return to an exactly critical condition, the changes in reactivity exactly offset each other, causing no change in the SDM.

A change in SDM in a critical reactor requires a change in boric acid concentration or a change in fission product poison concentration. A useful tool to evaluate changes in shutdown margin is to place reactivity parameters in two boxes. One box contains parameters that will instantaneously change at the time of the trip, i.e., rod position, power and coolant temperature. The other box contains parameters that will NOT instantaneously change at the time of the trip, i.e., boron, xenon, and samarium concentration.



If all of the changes are contained in one box, the SDM does not change. If changes occur in BOTH boxes, the SDM changes. If the SDM changes, the changes can be evaluated using equation 2.2-11.

2.2.5 Reactivity Anomaly

Technical specifications require that a reactivity balance be performed every 31 effective full power days to ensure that actual values of reactivity agree with the predicted values. The predicted values of reactivity are the values used in safety analyses. Any difference between the actual values and predicted values is called a reactivity anomaly. The maximum allowable value for a reactivity anomaly is 1% $\Delta K/K$. Since the predicted values are also used in the calculation of shutdown margins, nonconservative reactivity anomalies affect the safety of the plant.

2.2.6 Classroom Exercises

Exercise 1

Determine the estimated critical boron concentration for a startup 26 hours after shutdown. The desired rod position is control bank D at 60 steps. Use Attachment 2.2-1 and the following data:

<u>Prior to Shutdown</u>	<u>Shutdown Conditions</u>
Fuel Burnup = 100 EFPD RCS Boron = 800 ppm $T_{avg} = 577^{\circ}\text{F}$ Xenon Reactivity = Eq. for 100% Equilibrium Samarium Rod Position = CBD at 210 steps	RCS boron = 950 ppm Rod Position = SDBs withdrawn $T_{avg} = 547^{\circ}\text{F}$

Table 2.2-1 Rod Worths

Worth of all RCCAs	(-)7744 pcm
Worth of all Control Banks	(-)4068 pcm
Worth of all Shutdown Banks	(-)3676pcm
Worth of most reactive rod	(+)1040 pcm

Exercise 2

Initial Conditions:

Fuel Burnup = 100 EFPD

Rod Position = CBD at 220 steps

Xenon Reactivity = Eq. for 100%

Equilibrium Samarium

$T_{avg} = 577^{\circ}\text{F}$

Reactor power = 100%

RCS Boron = 750 ppm

1. Determine the shutdown margin using Attachment 2.2-2, Section I.
2. Assuming that a reactor trip has occurred and that the following conditions exist 40 hr after the trip, determine the shutdown margin using Attachment 2.2-2 Section II.

$T_{avg} = 547^{\circ}\text{F}$
RCS Boron = 750 ppm
3. Use Attachment 2.2-2, Section III, to answer the following questions. Assuming that the shutdown banks are withdrawn and no boron is added to the RCS:
 - a. Will the reactor go critical?
 - b. Will technical specification shutdown margin requirements be met?
 - c. Is the plant still in mode 3?
4. From the above condition, assume the licensee withdraws the shutdown banks, then takes no further action. What will happen over the next two days?

Exercise 3

The initial conditions are as stated in Exercise 2. The unit has tripped, and the residual heat removal system is to be placed in service when the RCS temperature reaches 300°F. The RCS is to be maintained at 300°F for the next four days. Using Attachment 2.2-2, Section IV, determine the boron concentration change required to meet the shutdown margin requirements for this condition.

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Attachment 2.2-1
Estimated Critical Condition Calculation (Delta Rho Method)

- A. Rod worth (pcm) at desired startup critical position
Bank ____ at ____ steps (Figure 2.2-1) (-) _____ pcm
- B. Rod worth (pcm) at last known critical condition
Bank ____ at ____ steps (Figure 2.2-1) (-) _____ pcm
- C. Algebraic difference = [A - B] () _____ pcm
- D. Power defect at last known critical condition (Figure 2.2-2) x (-1) (+) _____ pcm
NOTE: *Multiplication by (-1) accounts for reactivity change following reactor trip.*
- E. Present boron concentration _____ ppm
- F. Boron concentration at last known critical condition _____ ppm
- G. Boron worth (Figure 2.2-3) (-) _____ pcm/ppm
- H. Reactivity due to change in boron concentration = [(E-F) x G] () _____ pcm
- I. Xenon worth at time of startup criticality (Figure 2.2-4) (-) _____ pcm
- J. Xenon worth at last known critical condition (Figure 2.2-4) (-) _____ pcm
- K. Reactivity due to change in xenon concentration = [I - J] () _____ pcm
- L. Samarium worth at time of startup criticality (Figure 2.2-5) (-) _____ pcm
NOTE: *If shutdown less than 24 hr go to Line N and enter 0.*
- M. Samarium worth at last known critical condition (Figure 2.2-5) (-) _____ pcm
- N. Reactivity due to change in samarium concentration = [L - M] () _____ pcm
- O. TOTAL REACTIVITY CHANGE
(C) _____ + (D) _____ + (H) _____ + (K) _____ + (N) _____ = () _____ pcm

NOTE: *This is the reactivity change required for criticality at the rod height in Line A. If Line O is positive, boration is required. If line O is negative, then dilution is required.*

NOTE: *Since T_{avg} is required to be $>541^{\circ}F$, the reactivity change from moderator temperature is considered negligible.*

Attachment 2.2-1
Estimated Critical Condition Calculation (continued)

P. Boron concentration change $\frac{(O)}{(G)}$ = (Dilute/Borate) _____ ppm

Q. Reactivity anomaly calculation

Maximum position for criticality =

(A) _____ + 750 pcm = _____ pcm (Curve 1) Bank _____ Steps _____

Minimum position for criticality =

(A) _____ - 750 pcm = _____ pcm (Curve 1) Bank _____ Steps _____ OR

Rod insertion limit (technical specifications) Bank _____ Steps _____

Attachment 2.2-2

Shutdown Margin Calculation

Technical specification definition: SHUTDOWN MARGIN shall be the instantaneous amount of reactivity by which the reactor is subcritical or would be subcritical from its present condition assuming all full length rod cluster control assemblies (shutdown and control) are fully inserted except for the single rod cluster control assembly of highest reactivity worth, which is assumed to be fully withdrawn.

I. At-power SDM

- A. Total rod worth (Table 2.2-1) (-) _____ pcm
- B. Most reactive rod worth (Table 2.2-1) (+) _____ pcm
- C. Present rod worth
Bank _____ at _____ Steps (Figure 2.2-1) x (-1) (+) _____ pcm
NOTE: Multiplication by (-1) accounts for reactivity not available due to partial insertion.
- D. Present boron concentration _____ ppm
- E. Power defect
Reactor power _____ % (Figure 2.2-2) x (-1) (+) _____ pcm
NOTE: Multiplication by (-1) accounts for reactivity change following reactor trip.
- F. Total reactivity (Algebraic sum) () _____ pcm
NOTE: Technical specifications require that Line F be a negative value > 1300 pcm.

II. Post-trip SDM

- A. Reactivity total from line F, Section I () _____ pcm
- B. Reactivity changes since last known critical condition
 1. Xenon (Figure 2.2-4)
 - a. Present value (-) _____ pcm
 - b. Last known critical condition value (-) _____ pcm
 - c. Reactivity change = [a-b] () _____ pcm

Attachment 2.2-2
Shutdown Margin Calculation (continued)

2. Samarium (Figure 2.2-5)
- Present value (-) _____ pcm
 - Last known critical condition value (-) _____ pcm
 - Reactivity change = [a -b] () _____ pcm
3. Moderator Temperature
- Present value _____ °F
 - No-load value 547 °F
 - Temperature change (a -b) _____ °F
 - Moderator temp. coefficient (Figure 2.2-6) (-) _____ pcm/°F
 - Reactivity change = [c x d] () _____ pcm
4. Boron
- Present value _____ ppm
 - Last known critical condition value _____ ppm
 - Boron concentration change = [a -b] _____ ppm
 - Boron worth (Figure 2.2- 3) (-) _____ pcm/ppm
 - Reactivity change = [c x d] () _____ pcm
5. Algebraic sum
- (A) _____ + (B.1.c) _____ + (B.2.c) _____ +
(B.3.e) _____ + (B.4.e) _____ = () _____ pcm

NOTE: *Technical specification requirement for SHUTDOWN MARGIN in modes 1, 2, and 3: the algebraic sum must be a negative value > 1300 pcm.*

Attachment 2.2-2
Shutdown Margin Calculation (continued)

III. Actual shutdown reactivity with shutdown banks withdrawn

- A. Algebraic sum from B.5, Section II () _____ pcm
- B. Most reactive rod worth (Table 2.2-1) (-) _____ pcm
- C. Rod worth of shutdown banks (Table 2.2-1) (+) _____ pcm
- D. Actual shutdown reactivity = [A+B+C] () _____ pcm

CAUTION: *The definitions of OPERATIONAL MODES must be checked since they address the reactivity level of the core. Withdrawal of shutdown banks may cause a change in the OPERATIONAL MODE of the unit.*

IV. Plant Cooldown Reactivity Balance

- A. Complete Sections II.A, II.B.1, II.B.2, and II.B.3.

- B. Algebraic Sum

$$(II.A) \underline{\hspace{2cm}} + (II.B.1.c) \underline{\hspace{2cm}} + (II.B.2.c) \underline{\hspace{2cm}} + \\ (II.B.3.e) \underline{\hspace{2cm}} = \quad () \underline{\hspace{2cm}} \text{pcm}$$

- C. Shutdown margin requirement

- 1. Mode 3 (IV.B) $\underline{\hspace{2cm}}$ - (-1300) = () _____ pcm
- 2. Modes 4,5 (IV.B) $\underline{\hspace{2cm}}$ - (-1600) = () _____ pcm

NOTE: If C.1 or C.2 is positive, then boron addition is required.

- D. Boron concentration change

- 1. Boron Worth (Figure 2.2-3) _____ pcm/ppm

- 2. $= \frac{(C.1 \text{ or } C.2)}{D.1}$ _____ ppm

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INTEGRAL ROD WORTH vs. STEPS WITHDRAWN

BANKS B, C, & D 100 STEP OVERLAP BOL

HFP EQUILIBRIUM XENON CONDITION

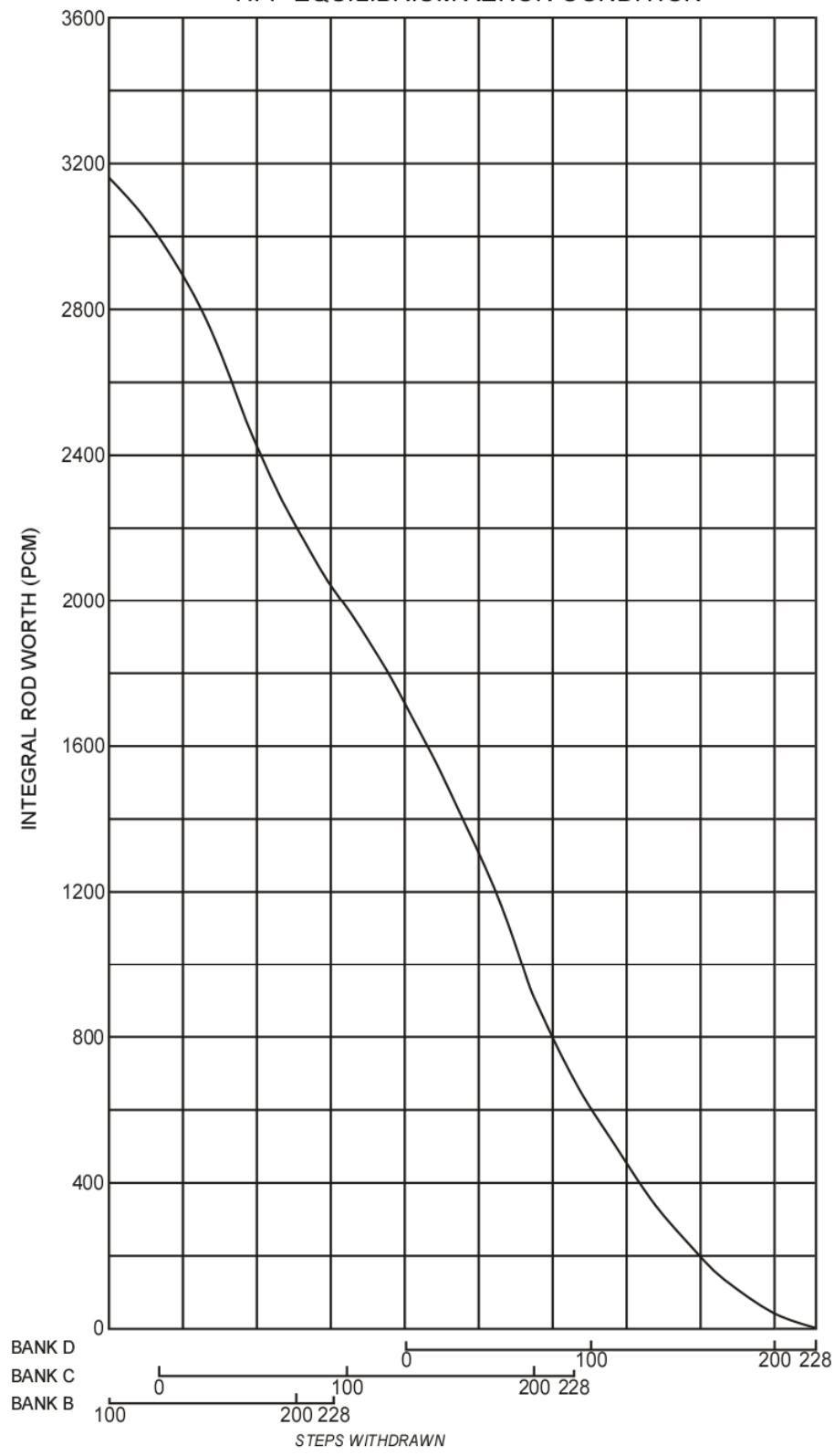


Figure 2.2.1 Rod Worth Curve

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**TOTAL POWER DEFECT
(DOPPLER & MODERATOR)
VS.
POWER**

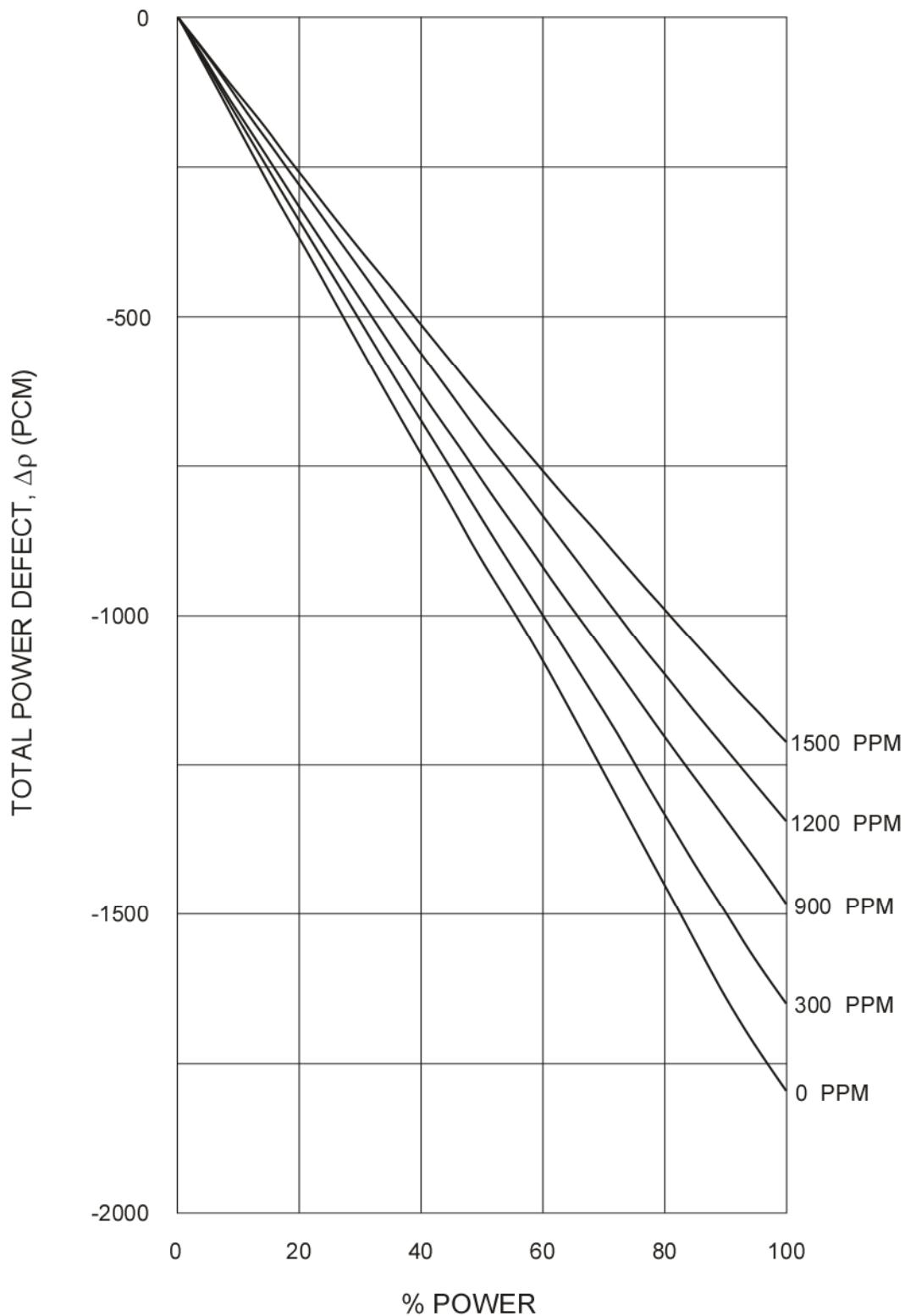


Figure 2.2-2 Total Power Defect

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DIFFERENTIAL BORON WORTH
VS.
BORON CONCENTRATION
AT VARIOUS MODERATOR TEMPERATURES
CYCLE 1, BOL

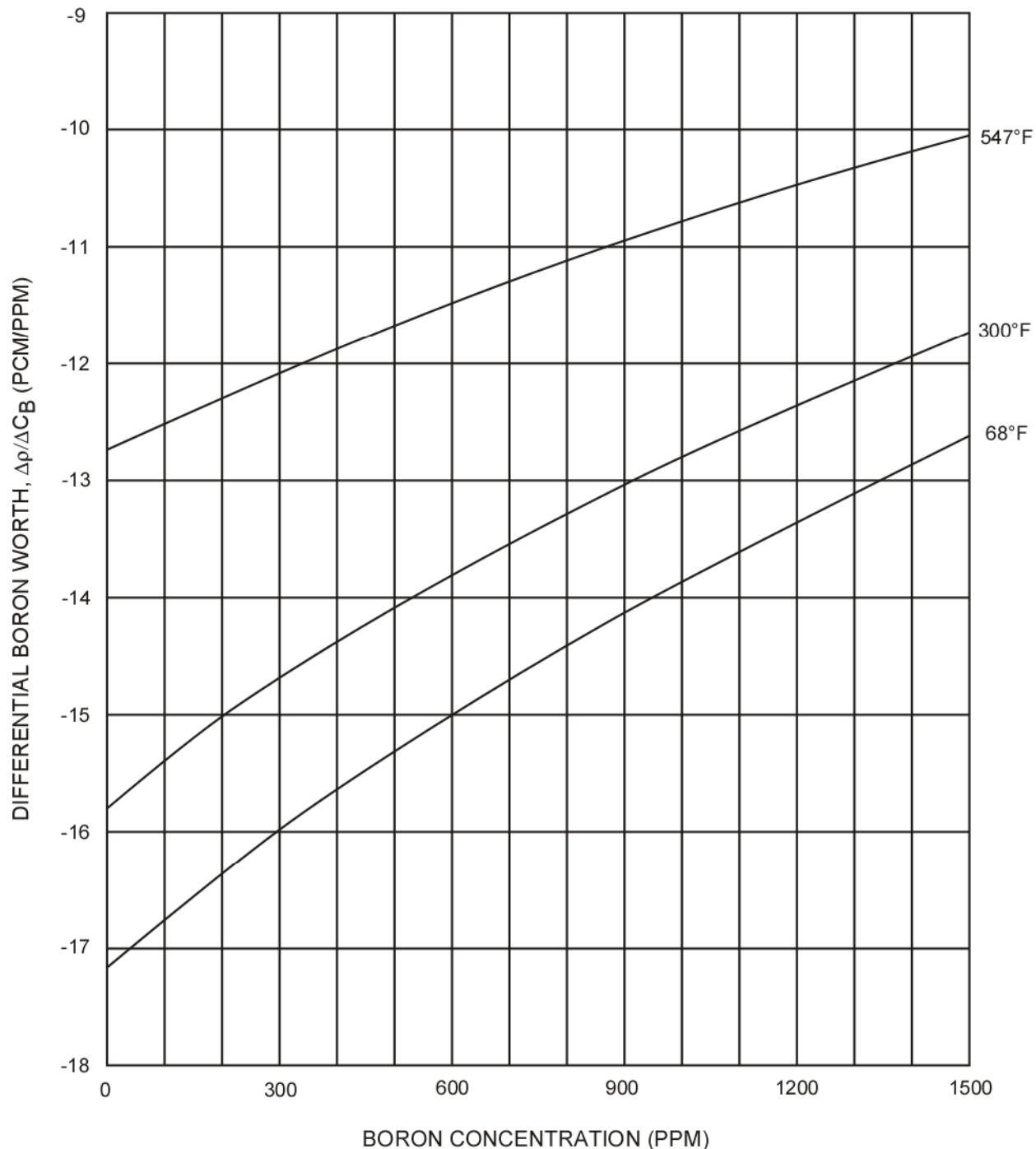


Figure 2.2-3 Boron Worth Curve

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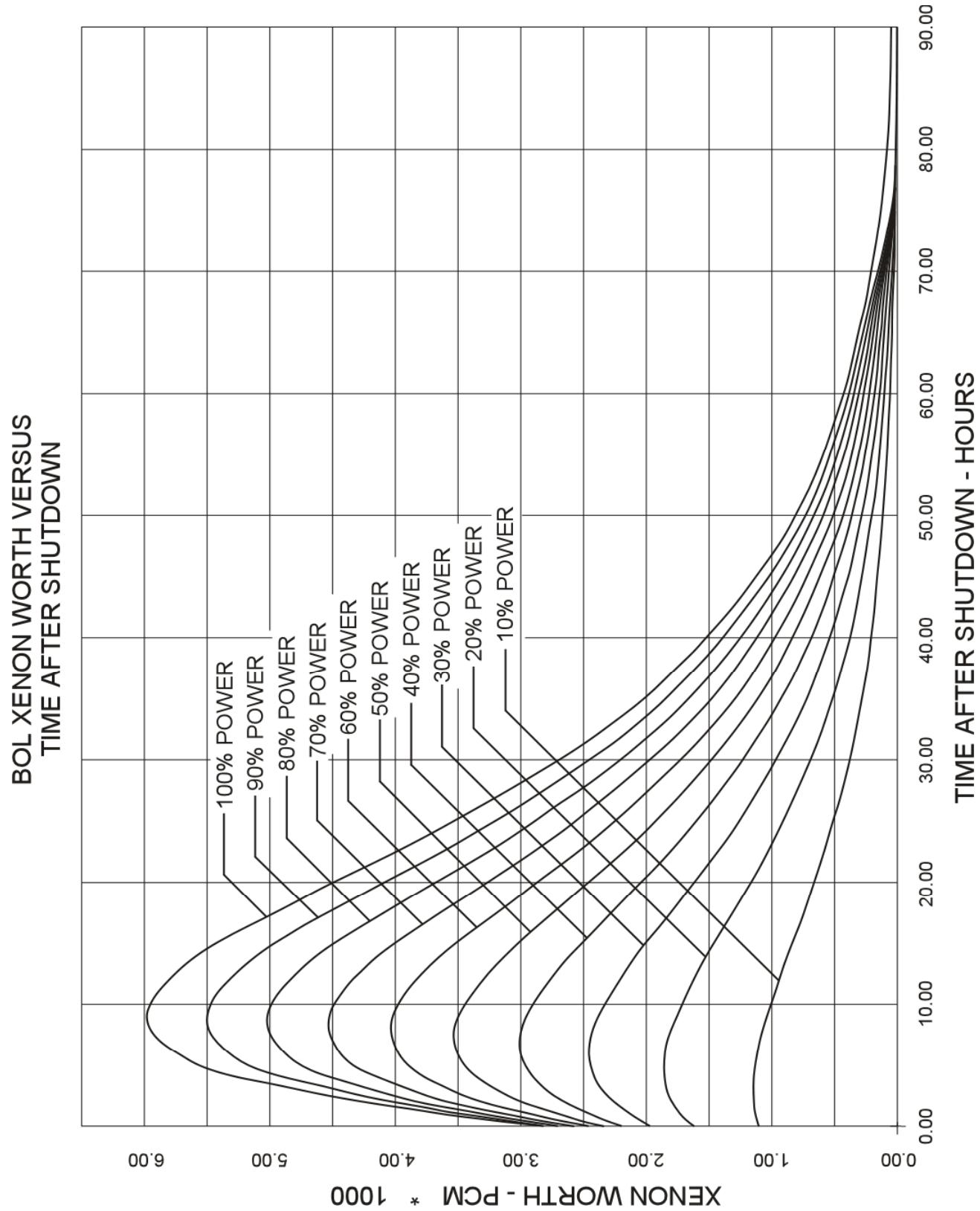


Figure 2.2-4 Xenon Worth Curve

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SAMARIUM REACTIVITY
AFTER SHUTDOWN FROM FULL POWER

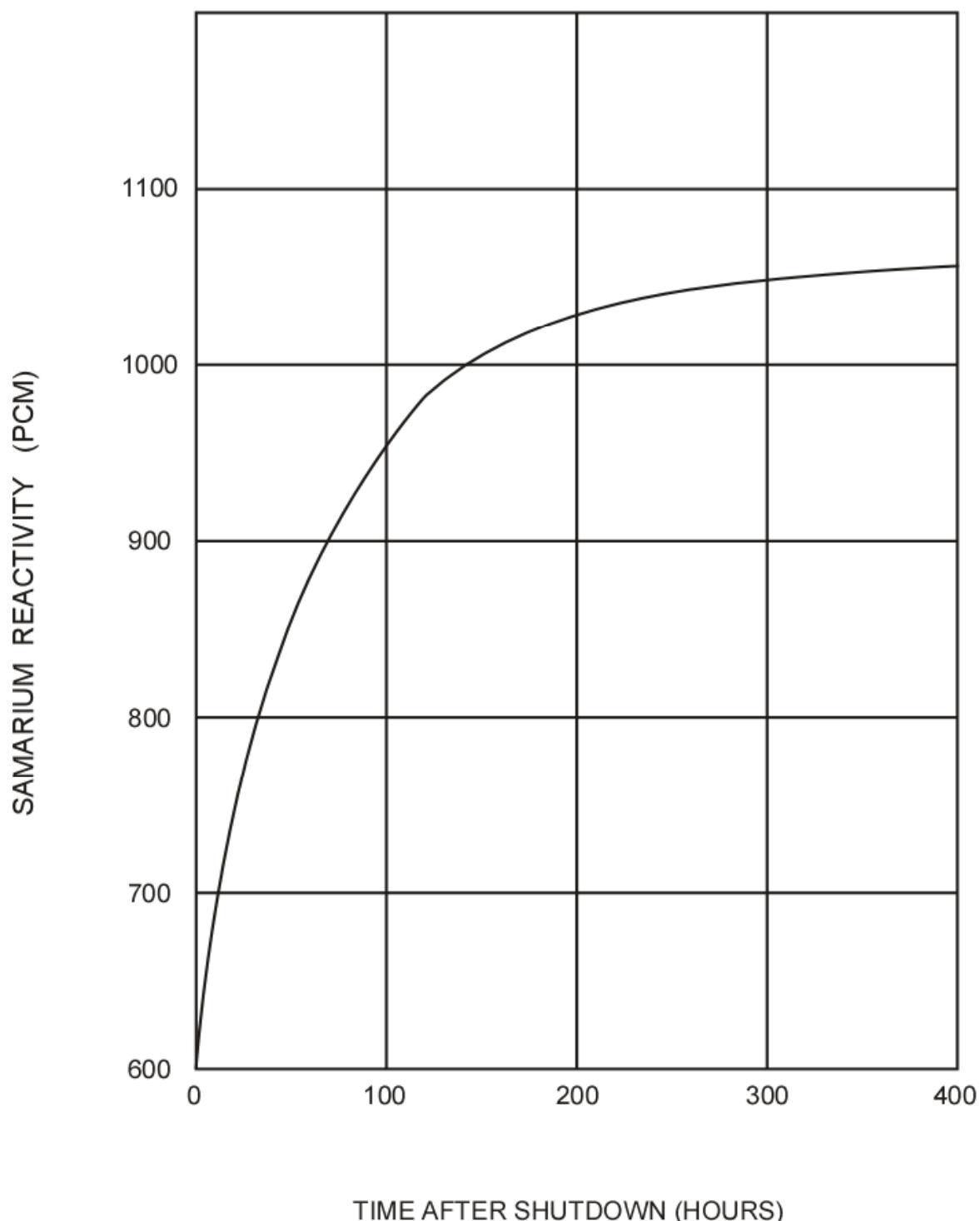


Figure 2.2-5 Samarium Worth Curve

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MODERATOR TEMPERATURE
COEFFICIENT
CYCLE 1, BOL, ARO

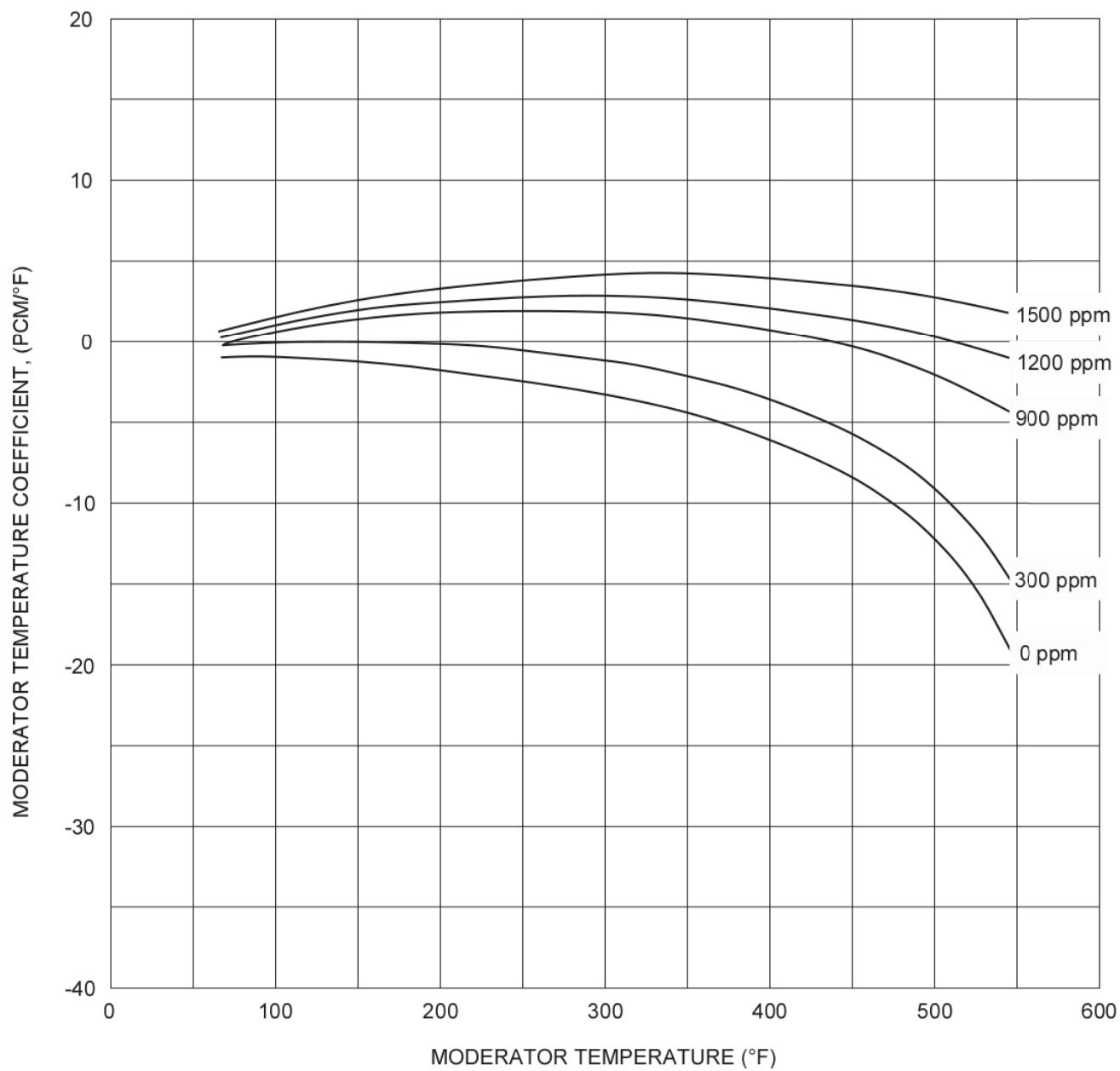


Figure 2.2-6 Moderator Temperature Coefficient

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